Jet A Fuel Vapor Flammability Program at Arizona State University

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Abstract

   Some basic aspects of fuel vapor ignition have been experimentally determined. The fuel vapor ignition temperatures for the lean ignition limits have been measured for jet-A fuels. The pressure ranged from 1 to 0.2 atm. corresponding to an altitude change from sea level to approximately 40,000 ft. Measurements were made with a induction-coil spark ignition circuit and a laser spark ignition system. Fuel loading has an important effect since the light ends in the fuel vapor diminishes in concentration at low fuel loadings, making the fuel vapor resistant to ignition. It may be possible to use the flashpoint as a reference temperature with which to apply a set of ignition data for a range of fuel batches. Contour maps of the ignition limits are being constructed for various fuel loadings, using both electrode- and laser- spark ignition systems, the latter having some well-defined spark characteristics.

INTRODUCTION Fuel vapor is present in the ullage (air space above the remaining fuel) of all fuel tanks. Fuel vapor can accumulate in fuel tanks as fuel consumption increases the empty volume in the tank. Under certain flight and ground conditions, the fuel vapor mixed with the available air in the tank is within flammable limits. For this reason, extreme care is taken to preclude ignition sources from fuel tanks. Because of this focus on excluding ignition sources, the flammability characteristics of jet fuels have not been examined in depth. Existing data include those of Nestor [1], Ott [2], and Kuchta [3]. Some recent work has been done Naegeli and Childress [4] and also by a Caltech group [5], but current data on ignition characteristics of jet fuels are far from complete.

        The work reported in this paper represents an attempt to provide the fundamental ignition characteristics of jet-A fuel vapor that can be applied to aircraft fuel tanks, with the knowledge of how various parameters such as spark deposition mode, electrode geometry, and thermo-fluid conditions for the fuel affect these ignition limits. For this phase of this research, we focus on the fuel loading effect, effect of flashpoint on ignition limits and ignition temperature mapping based on laser ignition tests. Laser ignition has been used in ignition research for the reason that the spark energy can be precisely controlled and measured, in addition to the fact that there are no complicating issues such as the thermal loss through the electrodes, electrode material and geometry effects.

EXPERIMENTAL METHODS A constant volume chamber has been used for determination of the ignition characteristics. It has an internal volume of 2.2 liters, and has a diameter and length of 125 mm and 400 mm, respectively. Temperature and pressure controls were accomplished by a set of temperature-controlled band-heaters and a vacuum pump, respectively. The vacuum pump was of a venturi type since the required variation was from 1 to ca. 0.1 atm. For the current testing, pressure from 1 atm down to 0.20 atm was considered, which corresponds to an altitude change from 0 ft to approximately 40,000 ft. Thermocouples were used to monitor both the fuel vapor and liquid bath temperature. The uniformity of the fuel vapor temperature was checked by traversing the thermocouple across the chamber, and proved to vary by less than 2 ^{O}F. The pressure transducer monitored the chamber pressure prior to ignition, as well as the pressure jump once the ignition has taken place. For the given chamber volume, a rang of liquid fuel volume was used for fuel vapor ignition tests, and indeed the fuel loading was found to have a significant effect as expected. The condition inside the test chamber was kept static. For each condition, the chamber pressure was set at a desired level, and a temperature controller was used to set the fuel vapor temperature. Once the chamber temperature had stabilized, an interval of 30 minutes was allowed for the fuel vapor to achieve liquid/vapor equilibrium. After the 30 minute period, sparks were applied for ignition. If ignition did not occur, the temperature was incremented and the procedure repeated. The ignition event was quite obvious from the pressure trace and also a noise caused by the sudden pressure increase. The temperature at which the ignition occurred was marked as the ignition temperature for that condition.

        The ignition sparks were generated using an induction-coil ignition circuitry and laser spark system. Further testing is on-going using a capacitance discharge system that allows for a variation in the spark energy

and duration. For the induction-coil system, the spark energy was determined using a high-voltage probe and a current meter. Once the voltage and current were known as a function of time, they could be integrated to give the spark energy. As noted above, the laser ignition systems are used in ignition research to provide a clean, quantifiable spark source. With a fundamental set of data using both laser- and electrode- ignition systems, the goal of this research is to relate such data sets to practical systems by linking them through real effects such as the electrode geometry, material and coating.
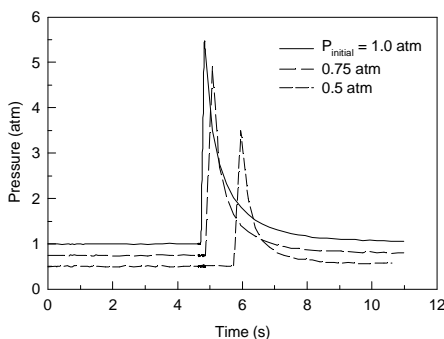

Figure 1. Typical pressure trace for ignited fuel vapor/air.

RESULTS AND DISCUSSION Figure 1 shows typical pressure traces obtained when the fuel vapor/air mixture was ignited. The ignition results in a sharp spike in the pressure trace, and the pressure increase is approximately a factor of six from the initial pressure. This corresponds to a temperature increase of a factor of six, consistent with the typical temperature increase during hydrocarbon combustion under constant-volume conditions. The ignition limit was defined as when there is such a pressure increase due to a full ignition of the fuel vapor.

The ignition limits of jet-A fuel vapor are shown in Figure 2. As expected, there is a substantial effect of the fuel loading on the ignition temperature. Available data on the fuel vapor pressure (the equilibrium partial pressure of the fuel vapor in air) show that the fuel vapor pressure increases with increasing fuel loading [5]. This means that there can be larger amount of fuel vapor for a fixed amount of air at a larger fuel loading. Since the test conditions involve lean ignition limits, i.e., fuel in less quantity than the stoichiometric amount, an increase in the fuel vapor mass means that the fuel-air ratio (or the equivalence ratio) is brought closer to the stoichiometric level. This makes the fuel-air mixture easier to ignite. Stoichiometric equivalence ratio corresponds to the fuel-air balance in the chemical reaction, and typically is associated with the lowest ignition temperature, peak flame temperature and largest flame speed. Therefore, at the fuel loading of 146 kg/m^3 (400 ml per 2.2 liter of chamber volume), the ignition temperature is the lowest for all pressure levels. However, more critical behavior is observed at low fuel loadings.

For example, Figure 3 is a re-plot of the above data that shows a direct dependence of the ignition temperature on the fuel loading. It can be observed that there is a steep increase in the ignition temperature when the fuel loading is brought below about 5 kg/m^3. As discussed above, this is due to some of the light ends being depleted so that the mixture becomes increasingly difficult to ignition at low fuel loadings, with other conditions being equal. This of course has an obvious yet important implications in both aircraft fuel tank operations in that one has to be aware of these critical limits so that a proper method for optimizing the safety can be devised. In short, the ignition is more difficult to achieve at very small fuel loadings, and beyond a certain limiting value the ignition temperature gradually decreases with increasing fuel loading.

Figure 4 shows the measurements of ignition temperatures similar to the data contained in Figure 2, except that a fixed fuel loading is used and a group of three fuel batches are used with the flashpoint ranging from 114 to 122 ^{o}F. For jet-A fuels, there is a wide range of flashpoints depending on the production origin, fuel weathering and other factors. For this reason, it would be of much importance to understand how a fundamental set of ignition data for a jet-A fuel batch can be applied to the entire range of fuel batches used in aviation. Figure 4 indicates an encouraging trend in this regard. If the ignition limits for various fuel batches are shifted by the flashpoint, i.e. if we use the flashpoint as a reference temperature, then the data nearly collapse to a single curve. There are further tests in progress to confirm this trend for a much wider range of flashpoints.
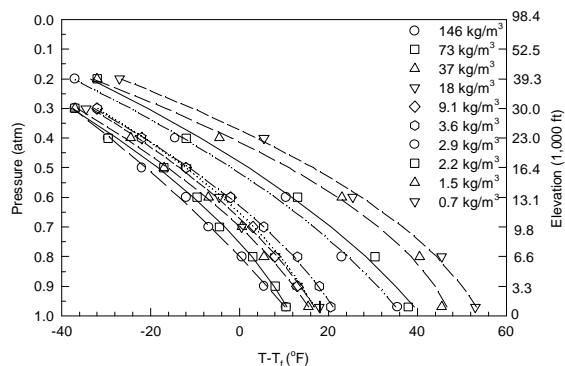
Figure 2. Ignition limits of jet-A fuel vapor at various fuel loadings. Inductance-coil ignition circuitry is used with the fuel flashpoint (T_{fp}) of 122 ^{o}F.
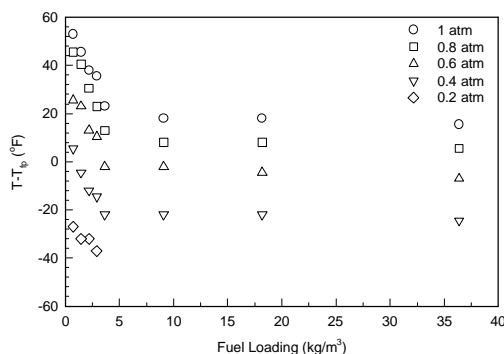

Figure 3. Plot of the ignition temperature as a function of fuel loading, based on the data in Figure 2.

Our current ongoing work of the fuel vapor composition using gas chromatography shows an interesting change in the relative concentrations of the many hydrocarbons species found in the jet-A fuel vapor. Some of these findings may confirm and explain the trends exhibited in Figures 2-4. For example, due to the relatively higher vapor pressures, only the light and intermediate hydrocarbons are found in vapor phase in comparison to the liquid phase. This of course means that the heavy hydrocarbon species may participate in the combustion processes once the jet-A fuel is ignited (e.g. in the combustion chamber), but the ignition processes would be essentially determined by the relatively light species in the vapor phase at the pressure and temperature conditions relevant for accidental ignition. More importantly, with respect to variations in the fuel loading, some of the hydrocarbon species undergo a much more dramatic change in the relative concentrations. Indeed, these may be the species that dictate the threshold for jet-A fuel vapor ignition.

Figure 5 contains the ignition temperature data plotted as a function of the ignition energy for the laser spark tests for a fuel loading of 37 kg/m^3. The spark energy can be measured by the difference between the incident and transmitted laser energy, which represents the net deposited energy. As expected, the jet-A fuel vapor is ignited at a given spark energy at much lower temperature at lower pressures or higher altitudes since the fuel vapor concentrations increase with decreasing pressure. There is a steep increase in the ignition temperature in the curves that run through the data points near 2 mJ at most of the pressures. This would correspond to the minimum required ignition energy for the given conditions. If the fuel vapor temperature is increased beyond this point, it actually requires a large spark energy as the fuel vapor is now moved into the fuel-rich region or so-called rich flammability limits.
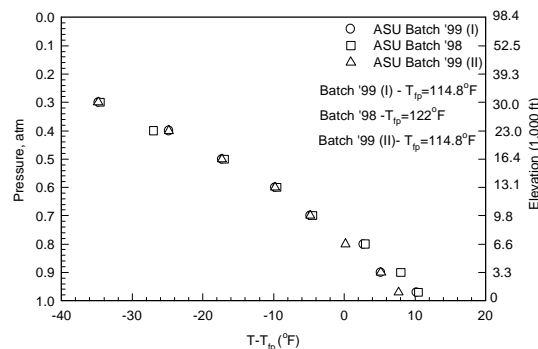
Figure 4. Use of flashpoint as a reference point to plot ignition limits of various fuel batches.
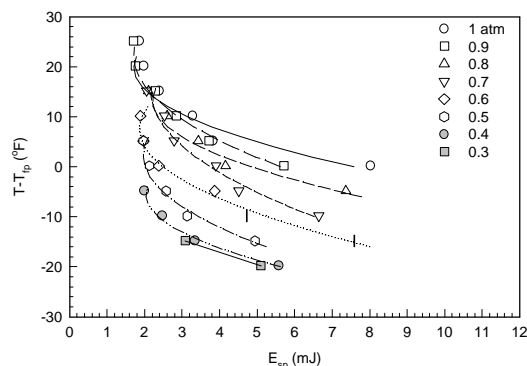

Figure 5. Ignition limits of jet-A fuel vapor as a function of the spark energy (laser spark experiments).

CONCLUSIONS   There are three major parameters that affect the ignition limits of jet-A fuel vapor. These are fuel vapor temperature, pressure and the fuel loading. The fuel loading shifts the ignition limits since at low fuel loadings, some of the light ends in the hydrocarbon species in the jet-A fuel vapor becomes depleted making the fuel-air mixture resistant to ignition. This change in the relative concentrations of the light ends are observable in the fuel vapor analyses. For a similar reason, the variations in the flashpoint of different jet-A fuel batches may be normalized by shifting the ignition limits by he flashpoint. For an intermediate fuel loading of 37 kg/m^3, the fuel vapor ignition temperature varies from +25 to –20 ^{o}F for pressure range of 1 to 0.3 atm and spark energy of 2 to 8 mJ.

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